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# An Overview of Geological Results from Mariner 9

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Mariner 9 acquired pictures of all of Mars at a resolution of 1–3 km; 1–2% of the planet is covered by pictures of 100- to 300-meter resolution. From these data, preliminary 1:5,000,000 scale photomosaics have been made of the entire planet, and a 1:25,000,000 scale shaded relief map published. Geologic maps of the planet have also been made at a variety of scales. The more than 7300 pictures acquired indicate that Mars is more varied and dynamic than previously inferred. About one half of the surface consists of ancient cratered terrain; the largest circular feature, Hellas, is almost twice the size of the largest basin on the moon, Imbrium. The remainder of the surface is covered either by younger volcanic rocks and constructs that stand as much as 17 km above the mean level or by extensive tracts of plains deposits, some of which are sedimentary in origin. The volcanic piles with summit calderas have fresh flank flows and appear to be geologically young. The great equatorial chasm or canyon system, comparable in size to the East African rift valley system, terminates in a complexly faulted plateau to the west and in large patches of chaotic terrain on the east. Large fluvial channels originate in this chaotic terrain possibly by melting of permafrost and appear to flow northward into the Chryse region. Other large sinuous channels with many tributaries have no such obvious source areas and many small dendritic channel networks abound in the equatorial regions and imply possible collection of rainfall. In addition, many small lava channels with distinctive characteristics are present like those on the moon and earth. Many of the basin floors are underlain by lava flows inferred to be basaltic from the form of the flows, ridges, and domes that characterize their surface. The polar regions are covered by glacio-eolian layered sediments that appear to be still forming under the present climatic regime. Older, layered, somewhat different deposits are being eroded into large pits and troughs around the margins of the poles. A mantle of eolian debris presumably derived from these eroded circumpolar zones thins equatorward. Both eolian erosional features such as yardangs and depositional features such as dunes have been identified. Eolian erosion and deposition processes are currently active, as is seen by numerous changes in the albedo patterns that were monitored after the clearing of the planet-wide dust storm. The largest planetary scale differences in crustal style are between the southern highlands, presumably underlain by less dense rocks, and the northern lowlands or 'oceanic' basins, underlain by more dense rocks. The greatest difference along the equator is between the high 'continental' block of the Tharsis ridge with its volcanoes aligned along its margin and the oceanic floor of the Amazonis basin in which the Nix Olympica volcanic pile lies.

This paper provides a summary of Mariner 9 mission operations insofar as they affected acquisition of geologic data. Selected results with a minimum of supporting evidence are presented to give, as briefly as possible, the geologic highlights of the mission. More detailed discussions of various regional and topical problems are given in other papers by various members of the television team. Also included are hypotheses inferred from preliminary evidence that will have to await the test of later geologic mapping and detailed topical studies. These hypotheses are included to call attention to areas in which potentially valuable work can be performed. It should be emphasized that many of the observations and hypotheses given have developed during discussions with many of the members of the Mariner 9 television team. My purpose here is to attempt a first distillation from the enormous body of facts and theory generated by the mission as a guide to the other papers in this issue and to present the most salient geologic results that distinguish Mars as a planet from both earth and the moon.

Mariner 9 was launched from Cape Kennedy on May 30, 1971, and was inserted into Mars orbit on November 13; the spacecraft continued to take pictures and to make measurements

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until October 27, 1972. More than 54 billion bits of information were transmitted to earth. More than 7300 pictures were taken of Mars and its satellites; about 1500 pictures of the planet were obtained by the 50-mm focal length wide-angle television camera, which has a resolution of 1–3 km [cf., *Masursky et al.*, 1970]. A preliminary map of the entire surface of Mars at a scale of 1:25,000,000 has been made from a mosaic of these pictures; a preliminary shaded relief map, the first detailed complete map of Mars, has been published at the same scale [*U.S. Geological Survey*, 1972].

The narrow-angle camera (500-mm focal length) acquired high-resolution pictures (100–300 meters) of between 1 and 2% of the surface. Geodesy pictures taken with the wide-angle camera from higher altitudes cover most of the southern hemisphere. These low-resolution pictures (4–9 km) were taken to provide control points for maps to be made from the high-resolution pictures. Thirty photomosaic maps at a scale of 1:5,000,000 have also been made for preliminary analysis and plotting of various types of data; later editions, based on improved control and use of enhanced pictures, have been made [*Batson*, 1973]; final maps will be made over the next several years.

Many pictures were taken to show time variations in cloud cover, polar cap frost, and the light and dark surface markings [*Sagan et al.*, 1973] on the planet. The infrared interferometer spectrometer [*Hanel et al.*, 1972] and ultraviolet spectrometer experiments [*Barth et al.*, 1972; *Hord et al.*, 1972], in addition to acquiring the atmospheric data, made pressure measurements from which the cartographers will attempt to compare integrated contour maps with occultation measurements [*Cain et al.*, 1973; *Kliore et al.*, 1972] and earth-based radar [*Downs et al.*, 1971; *Pettengill et al.*, 1971]. Systematic geologic mapping will be performed on the final cartographic products. Rectification, scaling, and additional enhancement of pictures and their integration with numerical results from the other experiments, such as gravity measurements provided by the celestial mechanics experimenters [*Lorell et al.*, 1973], will allow more sophisticated analysis, particularly of the thickness and density of the crust.

Because Mars is a low-contrast object, the pictures must be extensively computer enhanced to bring out surface detail. Suppression of electronic noise in the television subsystem and upgrading of enhancement techniques, especially early in the mission when dust in the atmosphere obscured the surface, allowed the image detail to be made visible [*Levinthal et al.*, 1973].

With the loss of Mariner 8, the extensively preplanned different but complementary objectives established for both spacecraft had to be integrated into a new mission plan for Mariner 9. On the arrival of Mariner 9 at Mars, the planetwide dust storm that had been observed in late September was still raging [*Capen and Martin*, 1971], so that this complex postlaunch mission plan also had to be abandoned. Reconnaissance pictures were taken until January 1, when the dust storm subsided sufficiently to begin mapping sequences, along with selected pictures taken for geodesy, variable features, atmosphere, and satellite studies. This mode continued with numerous successive modifications brought on by operational constraints until 70% of the planet had been mapped.

After a period of 2 months, during which pictures could not be taken because of solar occultation, the mapping mission was resumed. During this period the northern spring season progressed, and the north polar hood disappeared. Two new stars (Arcturus and Vega) were used for the first time in any space program to orient the spacecraft into more favorable picture-taking attitudes, thus allowing the remaining 30% of the planet in the northern hemisphere to be mapped. Some candidate landing sites for the Viking program in 1976 [*Soffen and Young*, 1972] also were photographed. After another interruption of 6 weeks during superior conjunction (Mars and the spacecraft passed behind the sun), the final extended mission picture sequences were taken to fill gaps in the photographic coverage, to photograph areas of special interest, to monitor the retreat of the north polar cap [*Soderblom et al.*, 1973*a*], and to study cloud formation over the volcanic constructs such as Nix Olympica [*Leovy et al.*, 1973].

## Volcanic Features

The first features that emerged through the dust pall that blanketed the planet were four

dark spots visible in high-altitude reconnaissance pictures; these spots later proved to be the four highest peaks on the planet, each of which is surmounted by a summit crater or complex of craters [*Masursky et al.*, 1972*a*, Figure 1]. Gradual atmospheric clearing revealed first the full extent of the great volcanic pile of Nix Olympica, which rises high above the Amazonis basin floor [*McCauley et al.*, 1972, Figure 10; *Carr*, 1973]. (Estimates of its height by various methods of altimetry vary from 8 to 27 km.) This single volcanic edifice is about twice as wide as the largest of the Hawaiian volcanic piles and is about equal in volume to the total extrusive mass of the Hawaiian Islands chain. The form of the flank flows and the lava channels with natural levees is strikingly similar to the form of those in Hawaii and the Galapagos, suggesting that the flows also may be basaltic in composition, as are those on these comparable terrestrial structures [*Simkin and Howard*, 1970; *Masursky et al.*, 1972*a*].

The three other volcanoes, also of surprisingly large size, lie along the Tharsis ridge. The summit of South Spot from current altimetry data lies more than 17 km above the floor of the Amazonis basin to the west. This estimated elevation difference almost equals the maximum relief on earth, which amounts to about 20 km. The lava flows that radiate from the summit caldera of South Spot are not long and thin, as are those of Nix Olympica, but rather are short and stubby [*Masursky et al.*, 1972*a*; *Carr*, 1973]. This difference in form suggests probable differences in the composition of the flank flows. Those of South Spot were clearly less fluid than those of Nix Olympica and may be more silicic, possibly andesitic in composition. Short, stubby flows of similar appearance are common in the upper parts of some continental volcanoes such as Mt. Hood and Mt. Rainier.

It is possible that variation in temperature and gas content, rather than a difference in original composition, could account for these differences in flow morphology. The lack of

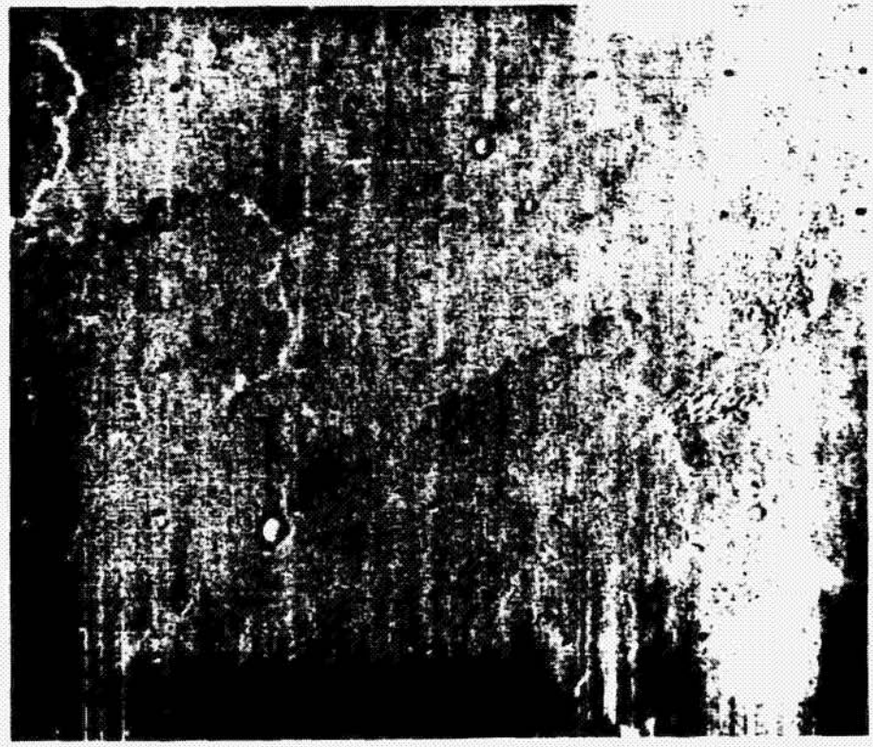

Fig. 1*a*. Lobate lava flow front on basin floor similar to basaltic flows on earth and the moon. (MTVS 4179-30, DAS 6966608.)

craters and the morphologic crispness of the lava flows indicate that the upper layers of these volcanoes are relatively young geologically, whatever their composition. The discovery of geologically youthful, large volcanic structures clearly indicates that Mars has been internally active. These features also provide a plausible source for much of the carbon dioxide and water in the atmosphere.

The Amazonis basin floor is covered in many places by a succession of lobate-fronted flows (Figure 1*a*) that resemble terrestrial basalt flows and the basalt flows that fill the mare basins on the moon (Figures 1*b* and 1*c*). Low mare-type domes with summit craters resemble basaltic shield volcanoes common on both the earth and the moon. Domes of this type are scattered over the basin floors in the Amazonis and Elysium regions [*McCauley et al.*, 1972; *Carr*, 1973].

In some areas the plains are slightly uplifted and transected by faults. Some of these closely spaced horsts and grabens are modified and often assume a streamlined appearance attributed to the long-term effects of eolian erosion [*McCauley*, 1973, Figures 2*a* and 2*b*]. Craters are more abundant in these structured terrains than on unfaulted plains; the most obvious of these faulted areas forms a large aureole around Nix Olympica. These rocks may represent an earlier generation of lava flows related to ancestral Nix Olympica volcanism [*Carr et al.*, 1973].

Another type of volcanic feature is exemplified in the Hesperia region (22°S, 253°W) [*Masursky et al.*, 1972*a*]. This feature is characterized by a line of calderas in the center of a pattern of circular and radiating faults and channels with irregularly distributed volcanic blankets. This unusual feature lies within an area of plains, and no large volcanic pile or constructional edifice is evident [*Carr*, 1973]. The channels closely resemble terrestrial and lunar lava channels. Another example of a volcanic

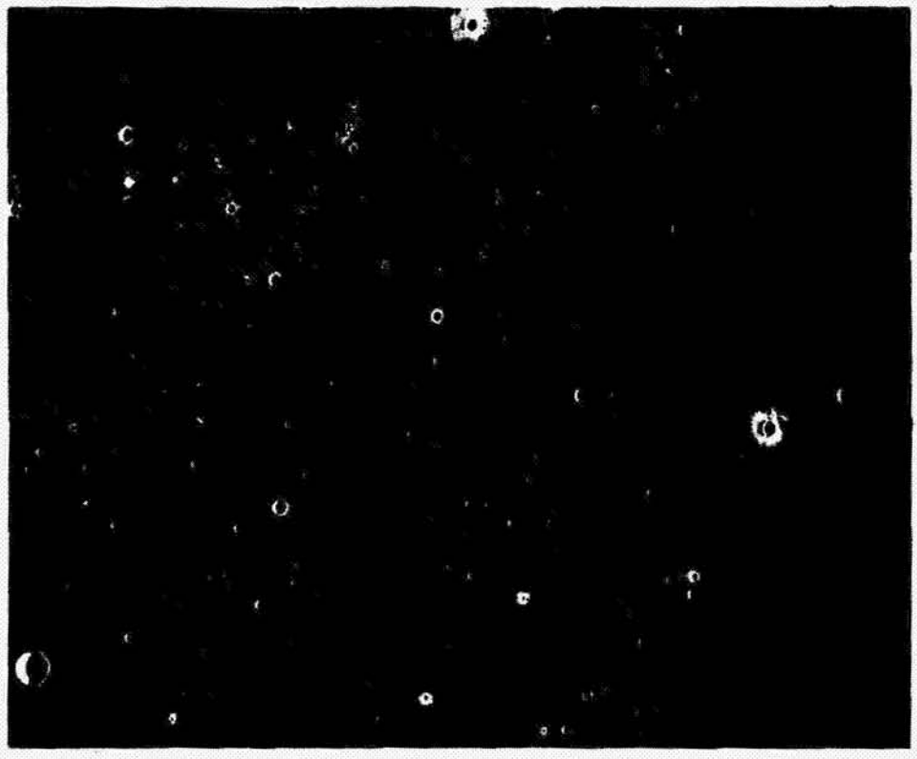

Fig. 1*b*. Lunar Orbiter 5 photograph showing lobate flow front on the moon in central part of Imbrium basin. Similar flows collected at the Apollo 15 landing site are basaltic in composition.

Fig. 1c. Elongate lava flows in northern Oceanus Procellarum photographed by the metric camera on Apollo 15.

feature lies in the Alba region (40°N, 110°W) (Figure 2*a*). Here an array of faults encircles a large depression in the central part of a very low prominence. This depression resembles a cauldron rather than a caldera. The morphology of these deposits and their relation to the tectonic features resemble those of terrestrial intracontinental volcanic centers such as those of Scotland [*Bailey et al.*, 1924; *Anderson*, 1937; *Richey*, 1961], Norway [*Oftedahl*, 1960], New England [*Kingsley*, 1931], and Africa [*Korn and Martin*, 1954] that contain more differentiated rocks of more variable composition than flood basalts and shield volcanoes. These terrestrial volcanic centers, when they are deeply eroded, commonly display ring and radial dikes, cone sheets, and evidence of cauldron subsidence.

Three other types of volcanic features are well developed. The first is typified by lines of craters 2–10 km in diameter along structural breaks parallel to major grabens [*McCauley et al.*, 1972, Figures 25 and 26]. Lines of volcanic vents such as the craters along the southwest rift zone of Mauna Loa, Hawaii [*McDonald and Hubbard*, 1970], are common in terrestrial areas with a similar structural pattern. The second type, which occurs in the floors of some Martian craters (Figure 2*b*) along fault zones, consists of polygonal blocks segmenting what appear to be frozen lava lakes in pit craters like those near the summit of Kilauea, Hawaii. Craters of this type also occur on the moon, where they have been called 'turtleback' craters (Figure 2*c*). The third type of volcanic feature consists of complex ridges that are commonly steeper on one side (Figures 3*a* and 3*b*). They occur in areas where lobate flow fronts and broad low domes imply basaltic volcanism. They resemble the lunar mare ridges that are interpreted as faults along which basaltic lava has squeezed upward. Similar squeezeups are common on terrestrial basalt flows but on a much smaller scale.

Fig. 2*a*. Mosaic of wide-angle pictures showing the complex of faults surrounding the volcanic structure in the Alba region. It resembles terrestrial volcanic complexes with central cauldrons. (MTVS 4224-63, DAS 8443019; MTVS 4222-69, DAS 83771129; MTVS 4222-57, DAS 83710849.)

## Tectonic Features

Sloping eastward from the Tharsis ridge crest is a large equatorial plateau or tableland. This plateau is broken by three sets of fractures trending east-west, northwest, and northeast. The paucity of craters indicates that the rocks underlying the plateau are geologically young. East of the mosaic of fault blocks, the grabens between blocks coalesce into the great equatorial canyon or rift valley system (Figure 4), 6 km deep in places, that extends almost 5000 km to the east (Figure 5*a*). Some volcanism associated with the inferred faulting that initiated these unanticipated Martian structures is suggested by the previously mentioned lines of craters along fractures parallel to the main rift valley system. These chain craters, however, lack obvious rim deposits and, alternatively, could be the product of collapse of surficial materials into subsurface fissures. The steep lateral valleys in places appear to be debris channels for mass wasted material. In other channels there are closed depressions that may be degraded volcanic vents. The upper reaches of the shallow sinuous valleys along the southern margin of the rift valley system appear to require formational processes other than mass wasting [*Masursky et al.*, 1972*b*]. Along the cliffs bounding the high plateau, layers and deposits are exposed that average about 100 meters in thickness. The uppermost

Fig. 2*b*. Polygonally broken filling of crater cut by fault. Filling is inferred to be volcanic and resembles terrestrial lava lakes that have solidified. (MTVS 4174-27, DAS 6822588.)

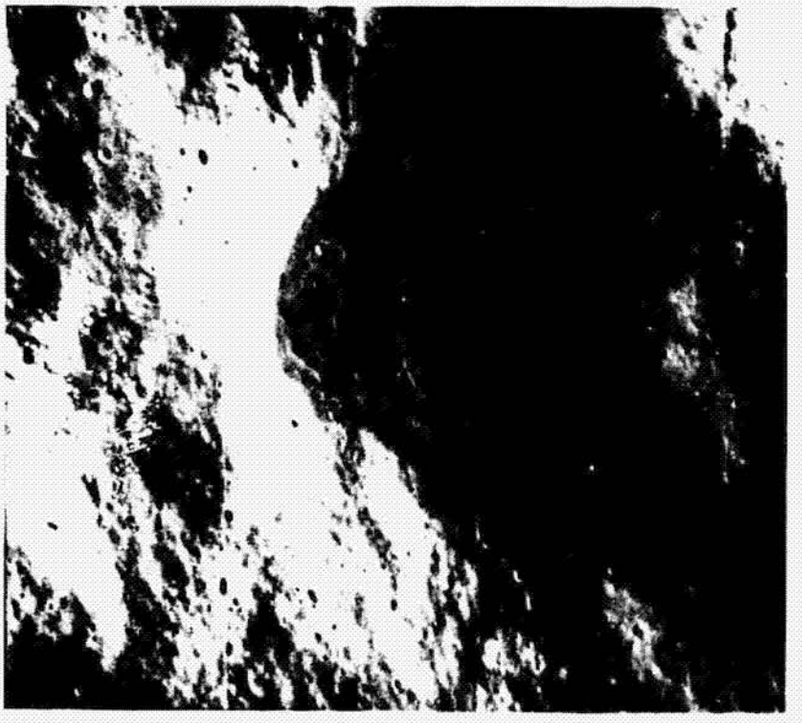

Fig. 2*c*. Turtleback lunar crater near crater Tycho photographed by Lunar Orbiter 5. Filling of crater inferred to be volcanic.

Fig. 3*a*. Wide-angle view of Middle Spot caldera. (MTVS 4081-3, DAS 3930239.)

Fig. 3*b*. Narrow-angle view of Middle Spot showing radiating fracture with accompanying extrusives similar to lunar mare ridges. (MTVS 4096-81, DAS 4402170.)

layer usually seems to be the most resistant and forms a rocky rim. The rocks may be volcanic, since they lie adjacent to the lines of craters that could be the feeder vents. In places, markedly eroded layers are visible within the canyon floors, and many layers of light and dark rocks are exposed (Figure 5*b*). The layers within these presumed valley fill deposits do not seem to match the more obscure and thicker layering in the canyon walls; thus these more

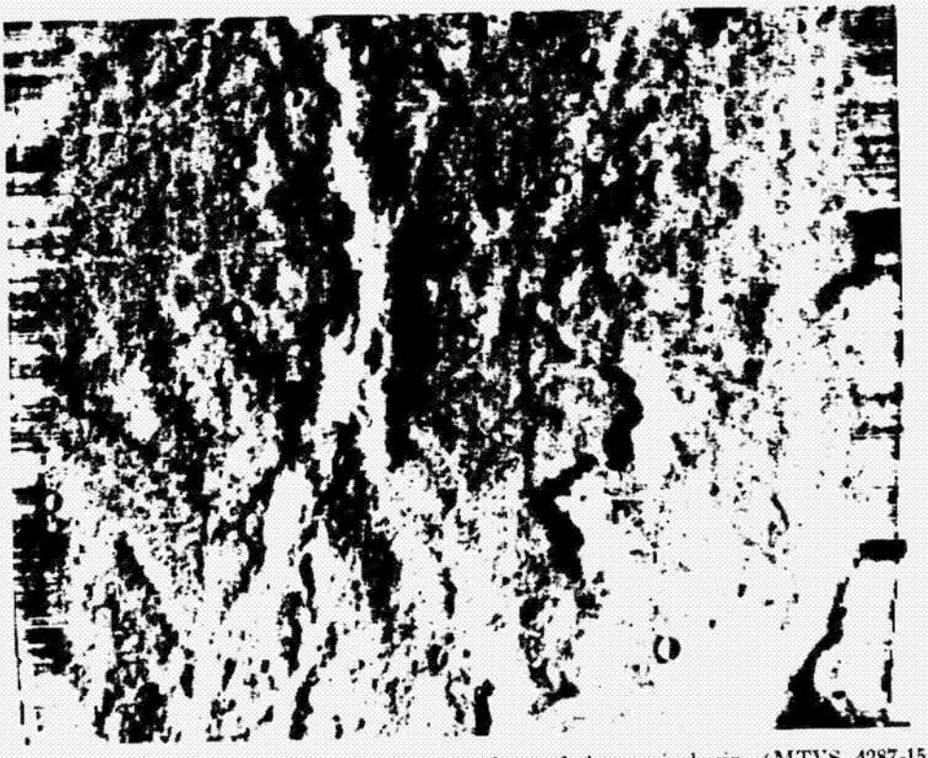

Fig. 3*c*. Complex fracture with extrusives on floor of Amazonis basin. (MTVS 4287-15, DAS 11443439.)

Fig. 4. Mosaic of Mariner 9 wide-angle pictures of the rift valley system.

finely layered deposits could represent earlier generations of valley fill now being stripped out by erosion. In many areas the cliffs are bordered by masses of debris that apparently have slid into the adjacent lowlands. In other areas the material retains its coherence and descends in a series of terraces similar in appearance to the chaotic terrain described in pictures taken by Mariner 6 and 7 [*Sharp*, 1973; *Sharp et al.*, 1971*a*, *b*].

## Channels

Emerging from the northern plateau lands, a complex array of broad sinuous channels descends into a regionally depressed area (Figures 6*a* and 6*b*). As the channels merge on the border of the flat low Chryse area, the channel floors show multiple braided channels and streamlined islands (Figure 6*c*) that confirm the northward direction of flow consistent with the regional slope of the surface determined from infrared and ultraviolet spectral data.

Lying on the level high plateau surface are other channels; these are sinuous and have many tributaries [*Masursky et al.*, 1972*c*, *d*; *Milton*, 1973]. The channels descend to the east and north, becoming broader and more clearly defined. The tributaries and the form of the braided channels are unlike those of terrestrial and lunar volcanic sinuous rilles and closely resemble terrestrial intermittent stream channels. Their form and degree of freshness strongly suggest flow of liquid water in the recent geologic past of Mars (Figure 7).

Some channels originate in great masses of hummocky to broken slabby material at the base of cliffs and may be related in origin to this chaotic terrain, as was proposed by *McCauley et al.* [1972] and *Masursky et al.* [1972*a*]. *Sharp et al.* [1971*a*] proposed from the Mariner 6 and 7 pictures that the collapse of these rocks and the formation of large-scale landslides may be caused by melting of permafrost. The more extensive photographic coverage leads to the logical extension of the permafrost proposal; that is, water derived from the melting of the permafrost seeped out from under the slides, formed the broad sinuous channels, and flowed into the northern lowlands. The only terrestrial analogs to these enormous channels, which are 30–60 km wide, are the channeled scablands of the Columbia plateau in the United States and the sandur plains (glacial outwash) of Iceland, which fringe the large glaciers [*Milton*, 1973]. In both areas, great volumes of glacial meltwater result in

torrential floods with accompanying fluviatil: erosion and deposition.

Two proposals have been made to account for the melting of permafrost over large areas. The first hypothesis is that local heating by volcanic activity would mobilize the fluids; the second proposes planetwide heating as a result of secular or cyclical changes in climate. A climate interglacial episode conceivably could melt the permafrost in the large equatorial region and thus be the cause not only of the chaotic terrain but also of the channels.

Somewhat different, very *sinuous* valleys with many tributaries lie on the high-level plateau surface in the Rasena, Mare Erythraeum, and Memnonia regions. The channels with braided floors descend to the east and north, becoming broader and more clearly defined [*Masursky et al.*, 1972*b*]. They apparently are formed by a different process than the broad chaos-related channels. Their primary and secondary tributaries, dendritic patterns, and lack of apparent source areas seem to require rainfall collected into integrated channels along with both surface erosion and deposition in alluvial basins.

Another type of channel is widespread in the ancient cratered terrain such as that near Sinus Sabaeus (8°S, 334°W). Complex networks of tiny coalescent channels run down the sides of many craters. Their origin is not unequivocal, but they also resemble fluvial channels and imply formation of precipitation collection. If this origin is correct, widespread rainfall is

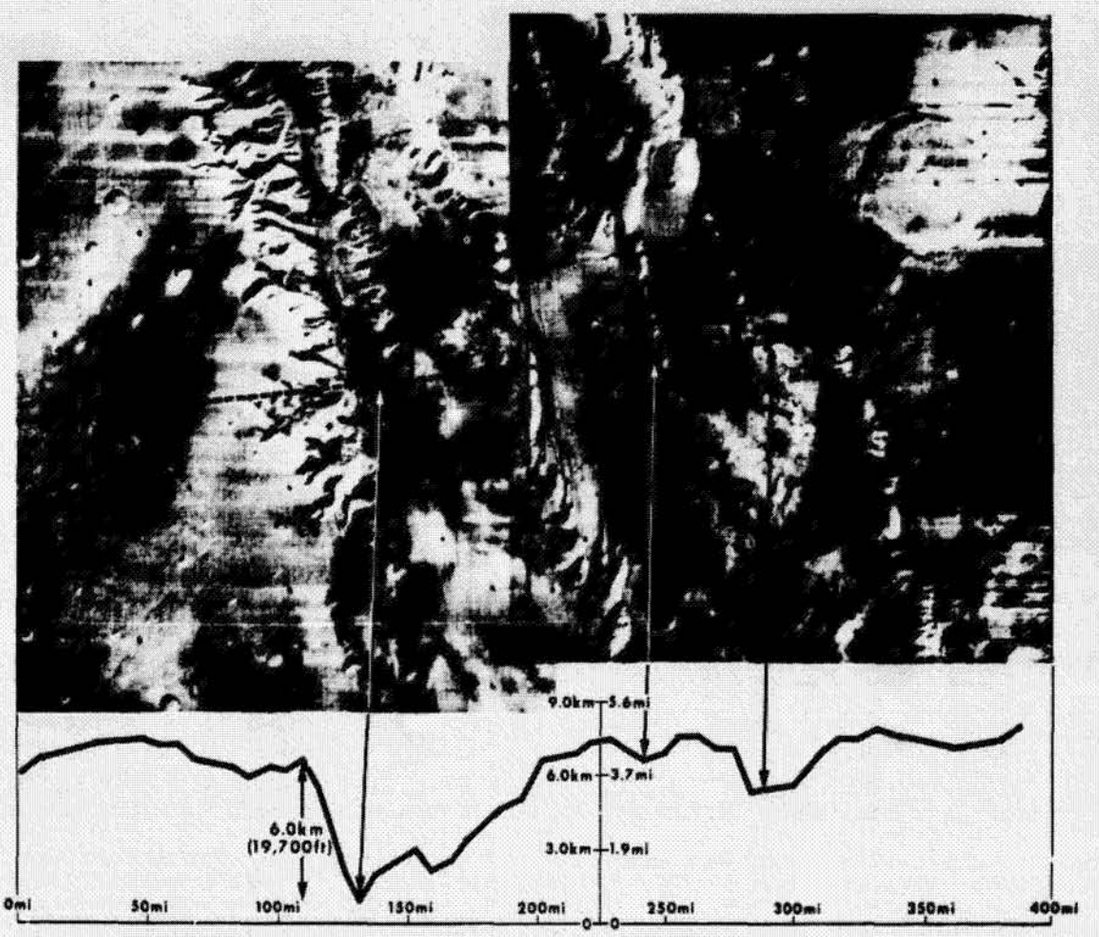


Fig. 5*a*. Inferred elevation profile across the rift valley system using pressure measurements made by the ultraviolet spectrometer [*Hord et al.*, 1973].

Fig. 5*b*. Light and dark layers in equatorial zone. Layers do not match the layers in the adjacent walls of the canyon and may be later fill now being stripped by erosion. (MTVS 4282-11, DAS 1049 2589.)

necessary to feed the channels. The occurrence of the channels in the equatorial zone suggests that only a slight temperature rise may be necessary to produce liquid water there, if the water partial pressure were to be raised at the same time. An 'interglacial' episode that melted the polar caps and planetwide permafrost should be adequate to allow flowing water to exist in the equatorial zone on the surface of Mars.

Another type of channel is associated with volcanic centers (Figure 8*a*). The channels start on the flanks of volcanic craters and are less well defined downstream. This relationship is the opposite of that generally observed in fluviatile channels. These features closely resemble lunar sinuous rilles such as the Hadley and Prinz rilles (Figure 8*b*) and are now generally thought to be collapsed lava channels in basaltic rocks, as is inferred from the samples and photographs returned by the Apollo 15 mission.

In summary, channels can be divided into four groups: the three varieties discussed with characteristics that imply a fluviatile origin in which water must be the transport medium (broad and sinuous, narrow with braided floors and tributaries, and small and closely spaced) and a fourth variety with characteristics that imply a volcanic origin involving molten lava flows.

## Polar Features

Monitoring of the polar regions allowed observation of the rapid retreat of the frost cover from its maximum extent of more than 50° across when it was photographed in 1969 to a minimum of less than 10° across in 1972 [*Masursky et al*, 1972*a*; *Soderblom et al.*, 1973*a*]. Ancient cratered terrain extends from north of the equator southward to the south polar region, where it is overlapped by two younger units (L. A. Soderblom, personal communication, 1972). The older of these overlying units is moderately cratered and has many closed depressions that appear to be deflation hollows (Figure 9*a*). This 'etch-pitted' unit is composed of alternating resistant and nonresis-

Fig. 6*a*. Mosaic of wide-angle pictures showing broad sinuous channels emerging from the base of the landslide debris and flowing north into the lowland.

tant rock layers that produce numerous topographic benches and slopes along exposed edges. The exposures of etch-pitted terrain surrounding the polar region indicate a zone of high wind velocity that is stripping the surface and forming deflation hollows. The etch-pitted unit is overlain by layered rocks originally termed the 'laminated terrain' (Figure 9*b*). The two units of young layered deposits do not overlie the ancient terrain in a platelike fashion. Although they total about 6 km in thickness, the central part lies at a lower elevation than the surrounding ancient cratered terrain covered by ice at the pole [*Hord et al.*, 1972]. Thus these layered rocks occupy a saucer-shaped depression that defines a discrete basin in both polar regions. It may be that the polar rocks have been depressed by formerly thicker polar ice. A quantitative measure of the degree of this deformation could be an indicator of the mobility of the Martian suberust.

The uniformly bedded layers best observed in the laminated terrain are estimated to range from 10 to 30 meters in thickness (L. A. Soderblom and J. A. Cutts, personal communication, 1972). There are about 20 layers in each cuestalike ridge, of which there are 6–12 encircling the pole. The individual thin layers appear to be cyclical deposits, as the groups of layers that form the ridges that showed in the Mariner 1969 pictures may be [*Sharp et al.*, 1971*b*]. The ledges are being eroded; the edges are smoothly rounded, unlike the sharp-edged ridges in the etch-pitted and central plateau

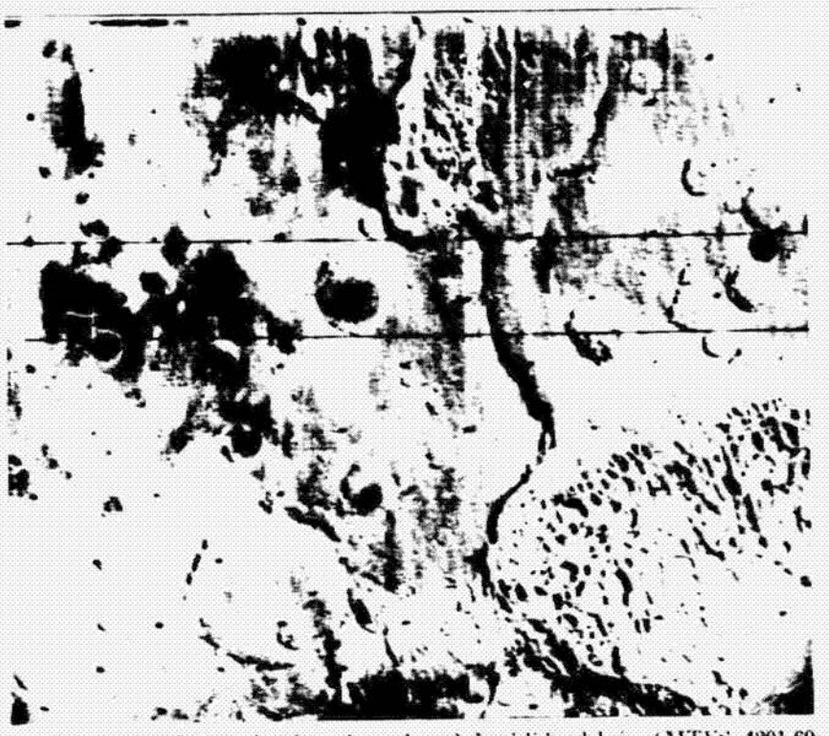

Fig. 6*b*. Wide-angle picture showing channel and landslide debris. (MTVS 4201-60, DAS 07686808.)

Fig. 6*c*. Braided channel with its source near the toe of a hummocky debris landslide. (MTVS 4206-63, DAS 07830588.)

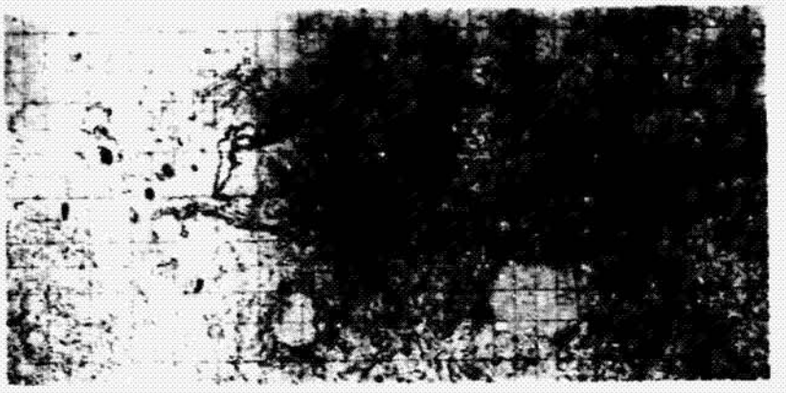


Fig. 7. Map showing the distribution of three fluviatile-type Mars channels.

regions. Subjacent craters are partially covered in many places; apparently they are being reexhumed after burial. The upper surfaces of these deposits on which the remnant polar ice cap lies are grooved radial to the pole [*Murasky et al.*, 1972b; *Cutts*, 1973]. These grooves may have been formed by wind erosion or perhaps even by glacial scour.

The south and north polar regions are similar (Figures 10 and 11) and apparently have acted

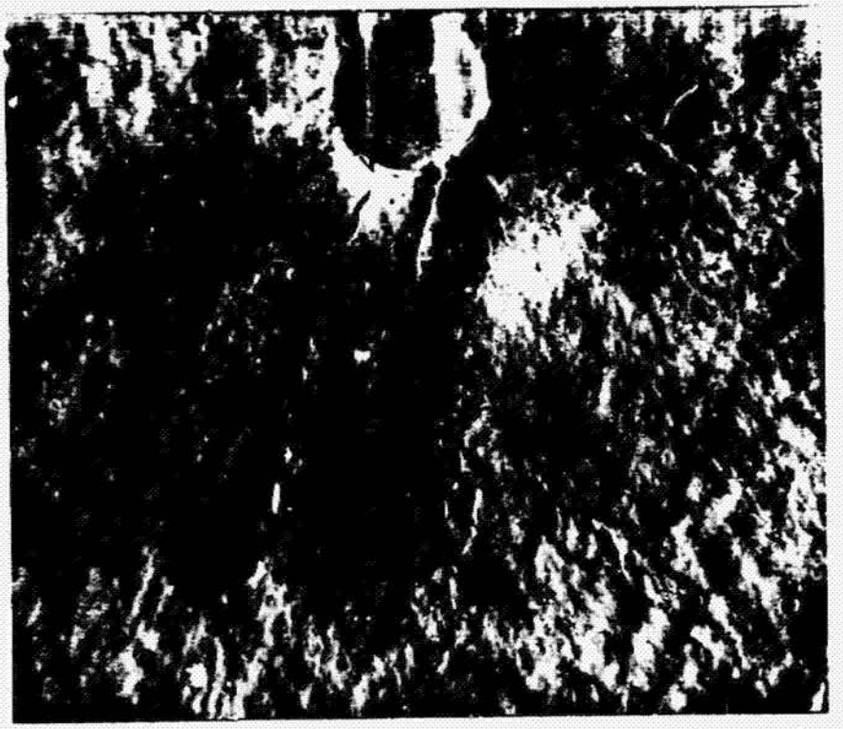

Fig. 8*a*. Lava channel on flank of crater; starts in crater and descends, becoming smaller in contrast to the fluviatile-type channels that grew downstream. (MTVS 4298-39, DAS 13496088.)

Fig. 8*b*. Priaz rilles in northwest part of moon photographed by Lunar Orbiter 5. The crater at the head of the rille is the side of the crater Priaz. It descends to the north, becoming narrower and shallower in contrast with the fluviatile-type channels on Mars.

as sediment traps throughout much of Mars history. Sedimentation in these areas must have started when the planet cooled enough to initiate frost accumulation in the polar region. Pervasive wind erosion in the equatorial regions took place; these sediments were then transported, principally in suspension, and deposited into the polar regions. The polar deposits may be thought of as glacio-eolian, formed when the dust particles acting as nuclei around which the snow crystals form are laid down as horizontal layers. A similar process takes place on earth when rain, wind, and snow sweep the atmosphere clean of dust particles. Alternatively, descending air currents in the polar high-pressure zone may abet the entrapment of dust particles on the surface ice, in much the same way as dust is entrapped in terrestrial ice fields and glaciers.

## Eolian Features

The planetwide dust storm appears to have blanketed much of the surface with bright silt and clay-sized particles, obscuring most of the dark markings normally observed telescopically. Since the end of the storm, bright material has been locally scoured from the surface and reveals the darker, presumably coarse-grained, underlying surface. During the mission a local dust storm was observed, and after its passage a dark track was visible [*Leovy et al.*, 1973]. As the mission progressed, the classic dark sur-

**Fig. 9*a*.** Etch-pitted terrain in the south polar region that overlies the ancient cratered terrain and is overlain by the laminated terrain. The closed depressions probably were made by deflation. The winds are particularly strong adjacent to the polar ice, as they are on earth in Antarctica and Greenland. (MTVS 4132-21, DAS 05453843.)

Fig. 9*b*. Laminated terrain in the south polar region overlain by residual ice. It eroded with rounded edges and was deposited cyclically. The short cycles comprise 8-10 layers, which make up ledges that form the circumpolar features. (MTVS 4213-21, DAS 08080243.)

face markings began to reemerge as the fine-grained and brighter surficial materials were scoured and redeposited [*Sagan et al.*, 1973].

Uniformly distributed deposits that fringe the polar regions and blanket the plains may correspond to terrestrial loess (widespread deposits of silt and clay-sized particles). Their redistribution reveals dark irregular markings and light and dark tails emanating from craters and other topographic obstacles. The light tails appear to be wind-deposited material; the dark tails appear to be mostly wind-scoured zones in the lee of various topographic obstacles. In other cases some dark streaks appear to be dark deposits.

In some areas dark markings in wide-angle pictures have been resolved into sand dune fields in the narrow-angle pictures [*Cutts and Smith*, 1973]. This dune field, about 50 km across, lies in the bottom of a crater. The spacing of the crests of individual dunes is of the order of 1–2 km. In size and shape this feature is similar to many dune fields and sand sheets in terrestrial deserts such as the Mojave Desert in southern California, within which the Kelso dune field is a good analog [*Sharp*, 1963]. Adjacent to the etch-pitted south polar terrain is an area of 'riffles,' which resemble longitudinal or seif dunes. Equatorward, in addition to the dune fields, the mottled cratered plains and smooth plains are areas of irregular to uniform eolian loesslike deposits that indicate even lower wind velocities. The identification of dunes is significant because dunes indicate that saltation is operative on the surface despite the tenuous atmosphere. With saltation occurring, numerous eolian erosion and deposition features should be expected at larger scales; some of these features are described by *McCauley* [1973] and compared with pure erosion forms in the coastal desert of Peru

## Impact Craters

Although impact craters are common on about one half of the planet's surface, fresh craters with well-developed ejecta blankets are

Fig. 10. Mosaic of wide-angle pictures of the south polar region showing the terrain units and residual cap. The polar deposits stand higher and overlie the ancient continental cratered terrain. The laminated deposits are deep inward and are topographically lower than the surrounding cratered terrain forming the polar basin.

**Fig. 11. Mosaic of wide-angle pictures of the north polar region showing the terrain and residual cap. The region lies 3 km lower than the south pole. The polar deposits lie on plains deposits of ocean basin type. The topography is not yet well enough known to determine whether the deposits are in a basin.**

rare [*Masursky et al.*, 1972*d*]. A few small craters show hummocky continuous ejecta blankets and well-developed rays. Most small craters, however, exhibit degraded ejecta blankets and no ray patterns.

Interpretation of lunar craters indicates that the first crater-related feature that disappears by erosion is the ray material, which originally extended outward for many crater diameters. The continuous ejecta blankets, up to two crater diameters in width, are more resistant to wind erosion. These deposits eventually lose their hummocky character, but the outer irregular edges remain as low ridges. The very slow degradation of craters on the moon is largely by impact gardening; on Mars the erosion is probably dominantly eolian. Most of the ray material of lunar craters and terrestrial experimental craters is fine grained; such material on Mars would be subject to degradation and transportation by winds. Thus the paucity of ray craters is an indicator of the effectiveness of the eolian erosional and depositional processes on Mars.

Prominent in the southern hemisphere of the planet are craters ranging from the limit of resolution (200–300 meters) up to the Hellas and Argyre basins. (Hellas is 2000 km in diameter and one half again the size of the Imbrium basin on the moon.) The cratering in this hemisphere is similar to that in the southern highlands of the near side and much of the far side of the moon [*Masursky et al.*, 1972*d*; *Wilhelms*, 1973]. The abundance of craters here is such that this terrain must be relatively older geologically. The crater frequency is less, however, than that on Phobos, the satellite of Mars, and in the most heavily cratered of the lunar uplands [*Hartmann*, 1973]. This lower crater frequency probably indicates destruction of some craters by various processes that include all previously mentioned (i.e., volcanism, tectonism, channel generation, and eolian erosion and deposition).

The Argyre basin is ringed by radially and concentrically textured mountainous terrain that indicates its similarity to the lunar multiringed impact basins such as Imbrium and

Orientale [*Hartmann and Kuiper*, 1962; *Hartmann and Wood*, 1971]. However, the deposits are altered by subsequent events, including eolian modification, so that they do not display the structural and depositional textures still preserved in the drastically less dynamic lunar environment [*Wilhelms and McCauley*, 1971]. Rough-textured, externally and internally terraced, generally circular craters with central peaks are thought, like those on the moon, to be of impact origin if they are not so degraded as to have these diagnostic characteristics obliterated.

Craters of impact type are clearly distinct from the smooth-rimmed volcanic craters with their commonly attendant radiating lava channels and flows. Secondary crater arrays are visible in several areas and are distinct from the linear arrays of volcanic craters along structural lineaments. They are, however, far less abundant than on the moon and generally cannot be identified as to source.

## Planetwide Distribution of Geologic Units

The cratered terrain apparently is the most ancient on Mars and probably records, as it does on the moon, the impact of cosmic debris on the early differentiated planet [*Masursky*, 1973; *Carr et al.*, 1973, Figure 1]. Preliminary correlation of gravity mapping achieved by tracking the Mariner 9 spacecraft with topography from several sources indicates that the lowlands and plateau regions previously described are largely isostatically compensated. This result is in agreement with the distribution of rocks on the moon, where the highlands are underlain by low-density crustal rocks with high Al/Si ratios and the lowlands are underlain by basalts that may rest directly on mantle rocks. For Mars, the cratered terrain that occupies most of the southern hemisphere may represent the more siliceous 'continental' crustal rocks. The Amazonis and adjacent Elysium basin and the northern lowlands may be underlain by basalts resting on the mantle and may be the gross equivalents of the terrestrial ocean basins and Oceanus Procellarum on the moon. Within the primitive cratered terrain are areas filled by smoother, younger material with lower, but still substantial, crater populations. These cratered plains are overlain by smooth deposits that form the plains, which comprise several different units. The smooth plains locally exhibit lobate laval flow fronts and broad low shield volcanoes attesting to the probable basaltic nature of the smooth deposits.

Mantling the smooth lava plains are possible alluvial deposits at the mouths of the channels in the Chryse and Lunae Palus regions. These deposits probably form piedmont alluvial and possibly playa sequences near where the channels debouche into the lowlands, so that some of the smooth plains may consist of sedimentary deposits. Pediplanation may have taken place in a few areas along channel margins and where plateau edges and isolated hills and mesas seem to be retreating [*Milton*, 1973].

Eolian deposits derived from the polar-eolian sediment traps may have been spread equatorward [*Soderblom et al.*, 1973*b*]. The thickness of these loess and dune deposits on the northern lava plains can be estimated from their apparent thickness in the south polar region. Here the mantling eolian material cannot exceed tens to hundreds of meters in thickness, for it partly but does not completely mask the south polar cratered terrain. Thinner deposits of eolian sediments (possibly silt and sand) cover the central part of the planet in places. Apparently these deposits in the central part of the planet are mobile, as the continually changing light and dark patterns monitored after the great dust storm attest. They must be only a few meters in thickness, as they do not obscure textural detail in the cratered and faulted terrain. Thicker loess deposits probably lie within Hellas and other similar large circular basins and craters, but their thickness cannot be determined; such regions do appear, however, to be the source areas for many Martian dust storms, including that of 1971 [*Capen and Martin*, 1971].

The south polar glacio-eolian deposits overlie the cratered terrain; the north polar deposits overlie smooth and cratered plains. The north polar region is about 3 km lower than the southern region (A. J. Kliore, personal communication, 1972). This observation is consistent with the morphology of the terrain, which suggests that the south polar region is part of the continental mass; the north polar region is part of the 'ocean' basin floor.

The margins of the central continental block are varied. At 100° to 130°W the margin is

abrupt and the slopes are steep; the crest of the Tharsis ridge is marked by the three aligned volcanic structures. Perhaps this continental margin is the site of incipient plate tectonic movement; alternatively, the volcanoes may lie along a zone of vertical movement bounding the continental block. The northern margin is irregular with gentler slopes. The contact between the cratered plains and the low-lying smooth plains is gradational and has many irregularly disposed hills and mesas. The central canyon or troughed zone may mark a rift zone developed by the highland rocks sliding into the northern lowlands; again alternatively, the canyons may mark complex vertical faulting, the most complex faulting being in the area of greatest uplift and adjacent to the thickest young volcanic rocks that overlie the continental crust.

## Geologic History

The various topical studies presented in this issue and the regional geologic mapping accomplished to date permit an expansion and synthesis of the earlier preliminary geologic histories presented for the equatorial belt [*McCauley et al.*, 1972; *Carr et al.*, 1973]. The principal data used are overlap relations between geologic units and differences in their crater populations. These relations show that Mars has a decipherable history that dates far back in time. This history may place some boundary conditions on theories about the evolution of its atmosphere and the development of an ice regime. The heavily cratered generally high-standing rocks that lie predominantly in the mid-latitudes and southern latitudes are the most ancient on the planet, as has been recognized since Mariner 6 and 7 [*Leighton and Murray*, 1971].

Large lunar basins such as Imbrium formed after the initial differentiation of the entire moon. Ejecta from these basins contain norites, anorthositic gabbros, and anorthosites that form the crustal rocks, which stand high because of their lesser density. A similar process probably took place on Mars, so that the high-standing heavily cratered rocks may be part of the early differentiated continental crust.

During a time of rapidly decreasing flux of impacting bodies, the many large flat-floored craters formed, as well as the large impact basins, Hellas, Argyre, and Libya. Hellas appears to be the oldest, as its rim has been almost completely destroyed and the number of superimposed craters around its edge is comparable to the rest of the heavily cratered terrain. Argyre and Libya are more rugged than Hellas and have fewer superimposed craters. They probably formed later.

Impact presumably continued at a decreasing rate, but volcanism started early in this episode. The oldest volcanic feature recognized is a volcano on the northeast rim of the Hellas basin (M. H. Carr, personal communication, 1972). This heavily cratered (it has twice as many craters as the oldest of the plains units) and eroded feature at first was difficult to recognize; other features may be found as systematic geologic analysis continues. The ancient volcano is of particular significance because it indicates that volcanism of the type observed in the Amazonis region began early in Mars history and within the ancient cratered terrain. Old plains units mantle parts of the ancient cratered terrain and are marked by lower crater frequencies. They are difficult to delineate because erosion and deposition have obscured their contacts. The oldest plains unit that can be mapped satisfactorily occurs in the Lunae Palus area and overlies part of the volanic structures in the Hesperia region. It has a greater crater density than most of the lunar maria. Its absolute age, like that of the other Martian units, is difficult to assess because the relative contributions to the flux of cometary and asteroidal impacts are not known.

Next younger in age are the heavily faulted plains around Nix Olympica, in Arcadia, and in Alba. They appear to be basalt flows, similar to those in the surrounding smooth plains, that have been slightly uplifted, faulted, heavily modified by eolian erosion, and moderately cratered. Mottled cratered terrain underlies large areas in the northern regions. It is moderately cratered and partly covered by eolian deposits. Volcanism probably started in the Nix Olympica area about the same time that these plains formed. The erosional scarp at the base of Nix Olympica suggests that these layers were being eroded while the upper part of the mountain was still being constructed. The next youngest plains unit occurs in the Phoenicis Lacus and Elysium areas. It is moderately cratered and faulted; the number of craters is

comparable to that on most lunar maria. It embays knobby terrain, indicating that the process forming the latter unit began before deposition of the moderately cratered plains.

Upwarping or epeirogeny then took place in the Tharsis region and resulted in mosaiclike fault patterns as well as the extensive rifting to the east in the main part of the Coprates canyon system. The upper part of the Nix Olympica as well as the Tharsis shield volcanoes then formed. Contemporaneously, the young lava plains with their abundant flow fronts and lava domes were extruded. Chaotic terrain developed later along the margins of the equatorial plateau. Broad channels then formed, apparently over a considerable time, since some of their floors are moderately cratered and others are little cratered. Their development may have paralleled the construction of the large volcanoes.

Eolian deposition and erosion extended over a considerable time up to the present; in the polar regions the laminated terrains were being deposited and eroded and redeposited in great mantles of sand and loesslike deposits that thin equatorward. Etch-pitted plains surrounding the poles attest to the intensity of eolian erosion of earlier deposits in the vicinity of the polar caps. This erosion raises the possibility that earlier generations of laminated terrain have been redistributed. The present polar deposits may record only the latest episode of deposition of layered materials.

The possible fluviatile channels may record episodes when water was much more abundant in the atmosphere than it is at present. Planet-wide warmer interglacial periods would release not only the water locked in the polar caps but also that frozen in the subsurface as permafrost. Similar warmer and colder periods also are characteristic of terrestrial history. Still continuing is the erosional modification of landforms and deposition of widespread silt and clay loess deposits and local sand dunes.

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